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FREQUENCY ERROR ESTIMATION AND FRAME SYNCHRONIZATION IN AN OFDM SYSTEM

BACKGROUND

I. Field

[0001] The present invention relates generally to data communication, and more specifically to techniques for performing frequency error estimation and frame synchronization in an orthogonal frequency division multiplexing (OFDM) communication system.

II. Background

[0002] OFDM is a multi-carrier modulation technique capable of providing high performance for some wireless environments. OFDM effectively partitions the overall system bandwidth into multiple (N_{sb}) orthogonal subbands, which are also commonly referred to as tones, sub-carriers, bins, and frequency channels. With OFDM, each subband is associated with a respective sub-carrier that may be modulated with data.

[0003] In an OFDM system, a transmitter initially codes, interleaves, and modulates a stream of information bits to obtain a stream of modulation symbols. In each OFDM symbol period, N_{sb} "transmit" symbols can be sent on the N_{sb} subbands, where each transmit symbol can be a data symbol (i.e., a modulation symbol for data), a pilot symbol (i.e., a modulation symbol for pilot), or a signal value of zero. The transmitter transforms the N_{sb} transmit symbols to the time domain using an inverse fast Fourier transform (IFFT) and obtains a "transformed" symbol that contains N_{sb} time-domain chips. To combat frequency selective fading (i.e., a frequency response that varies across the N_{sb} subbands), which is caused by multipath in a wireless channel, a portion of each transformed symbol is typically repeated. The repeated portion is often referred to as a cyclic prefix and includes N_{cp} chips. An OFDM symbol is formed by the transformed symbol and its cyclic prefix. Each OFDM symbol contains N_L chips (where $N_L = N_{sb} + N_{cp}$) and has a duration of N_L chip periods, which is one OFDM symbol period (or simply, "symbol period"). The transmitter may transmit the OFDM symbols in frames, with each frame containing multiple (N_{sym}) OFDM symbols. The frames of OFDM symbols are further processed and transmitted to a receiver.

[0004] The receiver performs the complementary processing and obtains N_L samples for each received OFDM symbol. The receiver removes the cyclic prefix from each received OFDM symbol to obtain a received transformed symbol. The receiver then transforms each received transformed symbol to the frequency domain using a fast Fourier transform (FFT) and obtains N_{sb} "received" symbols for the N_{sb} subbands, which are estimates of the N_{sb} transmit symbols.

[0005] The receiver typically performs frequency error estimation to determine the frequency error at the receiver. The frequency error may be due to a difference in the frequencies of the oscillators at the transmitter and receiver, Doppler shift, and so on. The receiver also typically performs frame synchronization to detect for the start of each frame so that a proper sequence of received symbols can be provided for demodulation, deinterleaving, and decoding.

[0006] To support frame synchronization, the transmitter typically transmits a training sequence across each frame. This training sequence contains pilot symbols and is transmitted on designated subbands. The receiver processes the training sequence to detect for the start of each frame. The training sequence represents overhead that reduces the efficiency of the system. Moreover, detection performance based on the training sequence is typically not robust, especially at low signal-to-noise ratio (SNR) conditions.

[0007] There is therefore a need in the art for techniques for performing frequency error estimation and frame synchronization in an OFDM system.

SUMMARY

[0008] Techniques for performing frequency error estimation and frame synchronization in an OFDM system are described herein. These techniques can provide good performance even at low SNR conditions and are based on a metric that is indicative of detected pilot power at the receiver. The metric may be defined in various manners depending on the method used for detecting pilot power. If channel gain estimates are not available, which is typically the case when frequency error estimation is performed, then the pilot power may be detected by (1) cross-correlating two received symbols obtained in two OFDM symbol periods (typically two received symbols for two consecutive OFDM symbol periods), for each of the pilot subbands used for pilot

transmission, and (2) accumulating the correlation results for all pilot subbands to obtain a decision statistic. The metric is then defined based on the decision statistic.

[0009] For frequency error estimation, a metric value is computed for each of multiple hypothesized frequency errors, which are different possible frequency errors at the receiver. The metric value with the largest magnitude among the metric values for the multiple hypothesized frequency errors is identified. The hypothesized frequency error for this identified metric value is provided as the estimated frequency error at the receiver.

[0010] For frame synchronization, a correlation value is obtained for each OFDM symbol period by correlating identified metric values obtained for N_C (e.g., most recent) OFDM symbol periods with N_C expected values. The expected values are computed in a manner consistent with the manner in which the metric values are computed. For example, if the pilot symbols for each pilot subband are scrambled with a pseudo-random number (PN) sequence by the transmitter and the metric values are obtained by cross-correlating pairs of received symbols, then the expected values are obtained by cross-correlating pairs of chips in the PN sequence. Peak detection is performed on the correlation values obtained for different OFDM symbol periods to determine frame synchronization.

[0011] Various aspects, embodiments, and features of the invention are described in further detail below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The features and nature of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

[0013] FIG. 1 shows a transmitter and a receiver in an OFDM system;

[0014] FIG. 2 illustrates pilot and data transmission for one frame using a frequency-time plane;

[0015] FIG. 3 shows a process for recovering the data symbols for each frame;

[0016] FIG. 4 illustrates the correlation of M_n metric values with a_n expected values for frame synchronization;

[0017] FIG. 5 shows a process for performing integer frequency error estimation;

[0018] FIG. 6 shows a process for performing frame synchronization;

[0019] FIG. 7 shows an OFDM demodulator at the receiver; and

[0020] FIG. 8 shows a specific design for the OFDM demodulator.

DETAILED DESCRIPTION

[0021] The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment or design described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or designs.

[0022] **FIG. 1** shows a block diagram of a transmitter 110 and a receiver 150 in an OFDM system 100. At transmitter 110, a transmit (TX) data processor 120 receives, formats, and codes traffic data (i.e., information bits) to obtain coded data. The coding increases the reliability of the data transmission and may include error detection (e.g., CRC) coding, forward error correction (e.g., convolutional, Turbo, and/or block) coding, or a combination thereof. The coding is typically performed for each data packet, which may have a fixed or variable length. TX data processor 120 then interleaves the coded data to obtain interleaved data. The interleaving provides time and/or frequency diversity against deleterious path effects and may also be performed for each data packet. TX data processor 120 next modulates (i.e., symbol maps) the interleaved data based on one or more modulation schemes (e.g., QPSK, M-PSK, M-QAM, and so on) to obtain data symbols. The same or different modulation schemes may be used for the data and pilot symbols.

[0023] An OFDM modulator 130 receives and processes the data and pilot symbols to obtain OFDM symbols. The processing by OFDM modulator 130 may include (1) multiplexing the data symbols, pilot symbols, and zero signal values onto data subbands, pilot subbands, and unused subbands, respectively, to obtain N_{sb} transmit symbols for the N_{sb} subbands for each OFDM symbol period, (2) transforming the N_{sb} transmit symbols for each OFDM symbol period with an N_{sb}-point IFFT to obtain a transformed symbol, and (3) appending a cyclic prefix to each transformed symbol to form a corresponding OFDM symbol. The pilot symbols may be multiplexed with the data symbols as described below. OFDM modulator 130 provides frames of OFDM symbols, where each frame contains N_{sym} OFDM symbols and may correspond to an integer number of data packets (e.g., one data packet).

[0024] A transmitter unit (TMTR) 132 receives and converts the OFDM symbols into one or more analog signals and further conditions (e.g., amplifies, filters, and frequency upconverts) the analog signal(s) to generate a modulated signal suitable for transmission over a wireless channel. The modulated signal is then transmitted via an antenna 134 to receiver 150.

[0025] At receiver 150, the transmitted signal is received by an antenna 152 and provided to a receiver unit (RCVR) 154. Receiver unit 154 conditions (e.g., filters, amplifies, and frequency downconverts) the received signal and digitizes the conditioned signal to obtain a stream of input samples. An OFDM demodulator 160 receives and processes the input samples to obtain received symbols. The processing by OFDM demodulator 160 may include (1) pre-processing the input samples as described below, (2) removing the cyclic prefix appended to each received OFDM symbol to obtain a received transformed symbol, and (3) transforming each received transformed symbol with an N_{sb}-point FFT to obtain N_{sb} received symbols for the N_S subbands. The N_{sb} received symbols for each OFDM symbol period include received data symbols for the data subbands and received pilot symbols for the pilot subbands. OFDM demodulator 160 also estimates and corrects for frequency error at the receiver, detects for the start of each frame, performs data detection, and provides a sequence of detected data symbols for each frame, as described below. A receive (RX) data processor 170 then demodulates, deinterleaves, and decodes the detected data symbols to provide decoded data. The processing by OFDM demodulator 160 and RX data processor 170 is complementary to that performed by OFDM modulator 130 and TX data processor 120, respectively, at transmitter 110.

[0026] Controllers 140 and 180 direct the operation at transmitter 110 and receiver 150, respectively. Memory units 142 and 182 provide storage for program codes and data used by controllers 140 and 180, respectively.

[0027] **FIG. 2** illustrates data and pilot transmission for one frame on a frequency-time plane 200. The vertical axis of plane 200 represents frequency and the horizontal axis represents time. The N_{sb} subbands are assigned indices of 1 through N_{sb} on the vertical axis. N_P subbands are used for pilot transmission, where in general $N_{sb} \geq N_P \geq 1$. The pilot subbands are indicated by the shaded boxes in FIG. 2 and may be distributed (e.g., uniformly) across the N_{sb} total subbands. The N_{sym} OFDM symbols for the frame are assigned indices of 1 through N_{sym} on the horizontal axis. Each

OFDM symbol includes N_{sb} transmit symbols for the N_{sb} subbands. In the following description, k is a subband index and n is an index for OFDM symbol and OFDM symbol period.

[0028] Different OFDM systems may use different values for the various parameters indicated in FIG. 2. As a specific example, an exemplary OFDM system may have an overall system bandwidth of $BW_{sys} = 6$ MHz, utilize an OFDM symbol with $N_{sb} = 4096$ subbands, allocate $N_P = 512$ subbands for pilot, use a cyclic prefix of $N_{cp} = 512$ chips, and have a frame length of one second. For this system, each subband has a bandwidth of $BW_{sb} = 1.46$ KHz (i.e., $6.0 \text{ MHz} / 4096$), each OFDM symbol has a length of $N_L = 4608$ chips (i.e., $4096 + 512$), each OFDM symbol period has a duration of 768 μsec (i.e., $4608 / 6.0 \times 10^6$), and each frame includes $N_{sym} = 1302$ OFDM symbols (i.e., $1.0 / 768 \times 10^{-6}$).

[0029] FIG. 2 also shows a frequency division multiplex (FDM) pilot transmission scheme in which pilot symbols are transmitted on pilot subbands and data symbols are transmitted on data subbands. The pilot subbands may be fixed for all OFDM symbol periods or may vary from symbol period to symbol period, frame to frame, and so on. The pilot transmission may also be sent continuously across an entire frame (as shown in FIG. 2) or may be sent only in some OFDM symbol periods. In any case, the subbands used for pilot transmission and the OFDM symbol periods in which the pilot is transmitted are known *a priori* by both the transmitter and receiver. For simplicity, the following description assumes that the pilot is transmitted continuously on designated pilot subbands, as shown in FIG. 2.

[0030] A sequence of N_P pilot symbols is transmitted on the N_P pilot subbands in one OFDM symbol period. The pilot symbol sequence is denoted as $\{p(k)\}$ and includes one pilot symbol for each pilot subband. The same pilot symbol sequence $\{p(k)\}$ is transmitted in each of the N_{sym} OFDM symbol periods for the frame.

[0031] To facilitate frame synchronization, the pilot symbols for each pilot subband are scrambled with a PN sequence. The PN sequence is denoted as $\{b_n\}$ and contains N_{sym} PN chips, where each PN chip is either +1 or −1 (i.e., $b_n \in \{1, -1\}$). For each pilot subband, the N_{sym} (same value) pilot symbols for the N_{sym} OFDM symbol periods for the frame are multiplied with the N_{sym} PN chips to obtain N_{sym} scrambled pilot symbols

for that pilot subband. The scrambled pilot symbol for each pilot subband of each OFDM symbol period may be expressed as:

$$P_n(k) = p(k) \cdot b_n \ , \qquad \text{for } k \in P \ , \qquad \text{Eq (1)}$$

where $P_n(k)$ is the scrambled pilot symbol for pilot subband k in symbol period n; and

P is the set of N_P pilot subbands.

N_P scrambled pilot symbol sequences are obtained for the N_P pilot subbands based on the N_P pilot symbols for these subbands and the same PN sequence. The scrambled pilot symbols are multiplexed with the data symbols, processed, and transmitted.

[0032] At the receiver, the received symbols after the FFT may be expressed as:

$$R_n(k) = S_n(k) \cdot H_n(k) \cdot e^{j(\theta + 2\pi f n N_L / N_{sb})} + N_n(k) \ , \qquad \text{Eq (2)}$$

where $S_n(k)$ is the transmit symbol for subband k in symbol period n;

$H_n(k)$ is the complex channel gain for subband k in symbol period n;

$N_n(k)$ is the noise for subband k in symbol period n;

$R_n(k)$ is the received symbol for subband k in symbol period n;

θ is an unknown phase offset that is constant across all N_{sb} subbands; and

f is a frequency offset (in integer number of subbands) to be estimated.

The transmit symbol $S_n(k)$ may be a pilot symbol $P_n(k)$ or a data symbol $D_n(k)$.

[0033] Equation (2) assumes that the fractional frequency error (i.e., of less than one subband) has been estimated and corrected prior to performing the FFT. Fractional frequency error of up to $\pm \mathrm{BW}_{\mathrm{sb}}/2$ can be estimated based on the cyclic prefix appended to each OFDM symbol or using some other techniques known in the art. Fractional frequency error causes inter-subband interference and is thus estimated and removed with a phase rotator prior to performing the FFT, as described below.

[0034] The frequency error f is a large frequency error that may be caused, for example, by different transmitter and receiver oscillator frequencies. The frequency error f is in integer number of subbands since the fractional portion has been corrected prior to the FFT. The integer frequency error f results in transmit symbol $S_n(k)$ sent on subband k being received on subband $k+f$, i.e., $S_n(k) \Rightarrow R_n(k+f)$. The entire

post-FFT spectrum at the receiver is thus shifted by f relative to the pre-IFFT spectrum at the transmitter. The integer frequency error only shifts the spectrum and does not cause inter-subband interference. This frequency error can thus be removed either prior to or after performing the FFT at the receiver. In the following description, "frequency error" and "frequency offset" are synonymous terms that are used interchangeably.

[0035] **FIG. 3** shows a flow diagram of a process 300 for recovering the transmit symbols $S_n(k)$ for a frame. Initially, the integer frequency error f is estimated based on a metric $M_n(f)$ and the received symbols $R_n(k)$, as described below (step 312). The estimated integer frequency error $\hat{f}$ is then removed to obtain frequency-corrected symbols $\tilde{S}_n(k)$, which include frequency-corrected data symbols $\tilde{D}_n(k)$ (i.e., received data symbols) for the data subbands and frequency-corrected pilot symbols $\tilde{P}_n(k)$ (i.e., received pilot symbols) for the pilot subbands (step 314). Frame synchronization is also performed based on the same metric $M_n(f)$ and the frequency-corrected pilot symbols (step 316).

[0036] Once the integer frequency error correction and the frame synchronization have been performed, the channel gain $H_n(k)$ can be estimated based on the frequency-corrected pilot symbols $\tilde{P}_n(k)$ (step 318). Data detection is then performed on the frequency-corrected data symbols $\tilde{D}_n(k)$ with the channel gain estimates $\hat{H}_n(k)$ to obtain detected data symbols $\hat{D}_n(k)$, which are estimates of the data symbols $D_n(k)$ sent by the transmitter (step 320). A proper sequence of detected data symbols for the frame is provided for subsequent processing (step 322). Each of the steps in FIG. 3 is described in further detail below.

[0037] For step 312 in FIG. 3, the integer frequency error f is estimated based on the metric $M_n(f)$, which is indicative of the detected pilot power at the receiver. The metric $M_n(f)$ may be defined in various manners, depending on the methods used to detect the pilot power. The receiver may use different methods for pilot power detection depending on whether or not channel gain estimates are available. Several pilot power detection methods are described below.

[0038] A cross-correlation method can be used to detect the received pilot power when channel gain estimates are not available at the receiver. This is typically the case

at the time the frequency error estimation is performed. For this method, decision statistics for different hypotheses of f may be expressed as:

$$A_n(\tilde{f}) = \sum_{k \in P} R_n(k+\tilde{f}) \cdot R_{n-1}^{*}(k+\tilde{f}) \cdot e^{-j2\pi\tilde{f}N_L/N_{sb}} \quad , \text{ for } \tilde{f} \in F \, , \qquad \text{Eq (3)}$$

where $\tilde{f}$ is a hypothesized frequency error;

$k+\tilde{f}$ is a hypothesized subband, which is offset by $\tilde{f}$ from pilot subband k;

$R_n(k+\tilde{f})$ is the received symbol for hypothesized subband $k+\tilde{f}$ in symbol period n;

$A_n(\tilde{f})$ is a decision statistic for hypothesized frequency error $\tilde{f}$ in symbol period n;

F is a set of hypothesized frequency errors to evaluate, i.e., $F = \{0, \pm 1 \ldots \pm f_{\max}\}$ where $f_{\max}$ is the maximum expected frequency error; and

" * " denotes the complex conjugate.

Each of the hypothesized frequency errors in set F is a different possible integer frequency error at the receiver.

[0039] In equation (3), the pilot symbols for pilot subband k are assumed to be shifted by the hypothesized frequency error $\tilde{f}$, and the received symbols $R_n(k+\tilde{f})$ and $R_{n-1}(k+\tilde{f})$ for the hypothesized subband $k+\tilde{f}$ (instead of the pilot subband k) are used for the decision statistic. Equation (3) effectively computes a cross-correlation between two received symbols for two consecutive OFDM symbol periods, i.e., $R_n(k+\tilde{f}) \cdot R_{n-1}^{*}(k+\tilde{f})$. This cross-correlation removes the effect of the wireless channel without requiring the channel gain estimate, which is typically not available yet. Equation (3) then accumulates the cross-correlation results for all N_P pilot subbands to obtain the decision statistic $A_n(\tilde{f})$ for the hypothesized frequency error $\tilde{f}$.

[0040] The exponential term $e^{-j2\pi\tilde{f}N_L/N_{sb}}$ in equation (3) accounts for phase difference (i.e., phase shift) between two consecutive OFDM symbols due to the hypothesized frequency error $\tilde{f}$. Different hypothesized frequency errors have different phase shifts. Equation (3) also assumes that the wireless channel is approximately constant or varies slowly over two OFDM symbol periods. This

assumption is generally true for most systems. The quality of the decision statistic $A_n(\tilde{f})$ simply degrades if the wireless channel varies more rapidly.

[0041] The decision statistic $A_n(\tilde{f})$ is computed for each of the different hypotheses of *f*. A set of decision statistics $A_n(\tilde{f})$, for $\tilde{f} \in F$, is obtained for all hypothesized frequency errors in set *F*.

[0042] The metric is defined as:

$$M_n(\tilde{f}) = \mathrm{Re}\{A_n(\tilde{f})\} \quad . \qquad \text{Eq (4)}$$

The decision statistic $A_n(\tilde{f})$ is generally a complex value and only the real part is used for the metric.

[0043] The integer frequency error can be estimated as the hypothesized frequency error that results in the maximum magnitude for the metric. This can be expressed as:

$$\hat{f}_n = \arg \max_{\tilde{f} \in F} \, | M_n(\tilde{f}) | \quad , \qquad \text{Eq (5)}$$

where $\hat{f}_n$ is the estimated integer frequency error determined at OFDM symbol period *n*. The metric can have both positive and negative values because the pilot symbols are scrambled by the PN sequence $\{a_n\}$. Taking the magnitude of the metric removes the effect of the scrambling.

[0044] The integer frequency error can be estimated either once using one pair of OFDM symbols or multiple times using multiple pairs of OFDM symbols. Frequency error typically varies slowly and the same estimated integer frequency error is often obtained for each OFDM symbol pair. Multiple estimates of the integer frequency error can be used to detect for a bad estimate and to provide greater confidence in the estimated integer frequency error. In any case, one estimated integer frequency error $\hat{f}$ is obtained for step 312. Furthermore, the integer frequency error estimation typically only needs to be performed once when the receiver first tunes to the transmitter and a large difference exists between the transmitter and receiver oscillator frequencies.

[0045] At the correct hypothesis *f*, the metric $M_n(f)$ may be expressed as:

$$M_n(f) = a_n \cdot \sum_{k \in P} | H_n(k+f) |^2 \cdot | p(k+f) |^2 + v_n(k+f) \quad , \qquad \text{Eq (6)}$$

where $v_n(k+f)$ is a noise term for $M_n(f)$ and may be expressed as:

$$v_n(k+f) = \mathrm{Re}\left\{ \sum_{k \in P} R_n(k+f) \cdot N_{n-1}^*(k+f) + R_{n-1}^*(k+f) \cdot N_n(k+f) \right\} , \qquad \text{Eq (7)}$$

and $\quad a_n = b_n \cdot b_{n-1}$, with $b_0 = b_{N_{sym}}$ and $a_n \in \{1, -1\}$. $\qquad$ Eq (8)

In equations (6) and (8), a_n is the correlation between two PN chips b_n and b_{n-1} for two consecutive OFDM symbol periods, where the PN sequence wraps around.

[0046] For an additive white Gaussian noise (AWGN) channel, the channel gain $H_n(k+f)$ can be omitted from equation (6). In this case, the SNR of the metric $M_n(f)$ at the correct hypothesis *f* may be expressed as:

$$\mathrm{SNR}_{fe} = \frac{(\mathrm{N_P} \cdot \mathrm{P_S})^2}{\mathrm{N_P} \cdot \sigma_v^2} = \mathrm{N_P} \cdot \frac{\mathrm{P_S}}{\sigma_n^2} , \qquad \text{Eq (9)}$$

where $\mathrm{P_S}$ is the transmit power for each pilot symbol, which is $\mathrm{P_S} = E\{|p_k|^2\}$, where $E\{x\}$ is the expected value of *x*;

σ_v^2 is the variance of the noise $v_n(k+f)$, which is $\sigma_v^2 = \sigma_n^2 \cdot \mathrm{P_S}$;

σ_n^2 is the variance of the noise $N_n(k)$;

$(\mathrm{N_P} \cdot \mathrm{P_S})^2$ is the signal power of the metric $M_n(f)$;

$\mathrm{N_P} \cdot \sigma_v^2$ is the noise power of the metric $M_n(f)$; and

SNR_{fe} is the SNR of the metric $M_n(f)$.

[0047] In equation (9), the ratio $\mathrm{P_S} / \sigma_n^2$ is also the SNR of the received data symbols. If the number of pilot subbands is sufficiently large, then the SNR of the metric $M_n(f)$ can be high even when the SNR of the received data symbols is low. For the exemplary OFDM system described above with $\mathrm{N_P} = 512$, the SNR of the metric $M_n(f)$ is approximately 27 dB when the SNR of the received data symbols is 0 dB (i.e., $\mathrm{SNR}_{fe} \approx 27$ dB when $\mathrm{P_S} / \sigma_n^2 = 0$ dB). The integer frequency error can thus be reliably estimated based on the metric $M_n(f)$ even at low SNR conditions.

[0048] In equation (3), the exponent term is used for phase correction due to the hypothesized frequency error $\tilde{f}$. A simplified decision statistic $A'_n(\tilde{f})$ may be defined without this phase correction term, as follows:

$$A'_n(\tilde{f}) = \sum_{k \in P} R_n(k+\tilde{f}) \cdot R^*_{n-1}(k+\tilde{f}) \ . \qquad \text{Eq (10)}$$

The metric may then be defined as $M_n(\tilde{f}) = A'_n(\tilde{f})$. The integer frequency error can be estimated as shown in equation (5). In general, $A'_n(\tilde{f})$ is a complex value and the square of the magnitude $|A'_n(\tilde{f})|^2$ (instead of the magnitude) can be more easily computed and used for equation (5). It can be shown that the SNR of the metric $M_n(f)$ defined based on $A'_n(\tilde{f})$ is approximately 3 dB worse than the SNR of the metric $M_n(f)$ defined based on $A_n(\tilde{f})$. This 3 dB degradation in SNR can be compensated by doubling the number of pilot subbands.

[0049] A matched filter method can be used to detect for the received pilot power when channel gain estimates are available at the receiver. For this method, the decision statistic may be defined as:

$$A''_n(\tilde{f}) = \sum_{k \in P} R_n(k+\tilde{f}) \cdot P^*_n(k) \cdot \hat{H}^*_n(k+\tilde{f}) \ , \text{ for } \tilde{f} \in F \ , \qquad \text{Eq (11)}$$

where $\hat{H}_n(k+\tilde{f})$ is the channel gain estimate for hypothesized subband $k+\tilde{f}$. In equation (11), the multiplication by $\hat{H}^*_n(k+\tilde{f})$ removes the effect of the wireless channel, and the multiplication by $P^*_n(k)$ removes the modulation on the pilot symbol. The metric $M_n(f)$ may then be defined to be equal to the real part of the decision statistic $A''_n(\tilde{f})$, i.e., $M_n(\tilde{f}) = \mathrm{Re}\{A''_n(\tilde{f})\}$, similar to that shown in equation (4). Other methods may also be used to detect for the received pilot power. The metric is defined based on the decision statistics provided by these methods.

[0050] For step 314 in FIG. 3, the estimated integer frequency error $\hat{f}$ is removed to obtain the frequency-corrected symbols $\tilde{S}_n(k)$. The integer frequency error correction may be performed either prior to or after the FFT at the receiver. For post-FFT frequency error correction, the received symbols $R_n(k)$ are simply translated by $\hat{f}$

subbands, and the frequency-corrected symbols $\tilde{S}_n(k)$ are obtained as $\tilde{S}_n(k) = R_n(k+\hat{f})$, for all applicable values of k. For pre-FFT frequency error correction, the estimated integer frequency error $\hat{f}$ can be combined with the fractional frequency error to obtain the total frequency error. The input samples are then phase rotated by the total frequency error, and the FFT is performed on the phase-rotated samples. The frequency of the receiver oscillator can also be adjusted by a phase-locked loop (PLL) to correct for the estimated frequency error $\hat{f}$.

[0051] For step 316 in FIG. 3, frame synchronization is performed based on (1) the same metric $M_n(f)$ used for frequency error estimation and (2) the frequency-corrected pilot symbols $\tilde{P}_n(k)$. The frequency error estimation in step 312 provides the maximum metric value M_n for each OFDM symbol period n, which can be expressed as:

$$M_n = M_n(\hat{f}) \, , \qquad \text{Eq (12)}$$

where $M_n(\hat{f})$ may be defined based on either $A_n(\tilde{f})$ or $A'_n(\tilde{f})$. The simplified decision statistic $A'_n(\tilde{f})$ may be used if the integer frequency error is corrected prior to performing the FFT. The M_n metric values are obtained based on the frequency-corrected pilot symbols by the frequency error estimation.

[0052] A cross-correlation between the M_n and a_n values is performed for each OFDM symbol period, as follows:

$$C_n = \sum_{i=0}^{\mathrm{N_C}-1} M_{n-i} \cdot a_{\mathrm{N_C}-i} \, , \qquad \text{Eq (13)}$$

where $\mathrm{N_C}$ is the length of the correlation, which is $\mathrm{N_L} \geq \mathrm{N_C} \geq 1$; and

C_n is the result of the cross-correlation between (1) the M_n values for the $\mathrm{N_C}$ most recent OFDM symbol periods and (2) the a_n values for the first $\mathrm{N_C}$ OFDM symbol periods in each frame.

[0053] **FIG. 4** illustrates the correlation between the M_n and a_n values. A truncated sequence with the first $\mathrm{N_C}$ a_n values for a frame is shown at the top of FIG. 4 and given indices of 1 through $\mathrm{N_C}$. A sequence with the $\mathrm{N_C}+1$ most recent M_n values are shown in the middle of FIG. 4 and given indices of $n-\mathrm{N_C}$ through n. For each OFDM

symbol period n, one C_n correlation value is obtained by correlating the truncated a_n sequence with the M_n sequence for the OFDM symbol period. The M_n sequence effectively shifts to the left when a new M_n value is obtained for the next OFDM symbol period. The a_n sequence remains stationary.

[0054] The a_n values are the expected values for the M_n values. For the embodiment described above, the a_n values are defined as $a_n = b_n \cdot b_{n-1}$ because the M_n values are obtained by correlating two consecutive received pilot symbols that are scrambled with two PN chips b_n and b_{n-1}. For this embodiment, enhanced performance for frame synchronization may be achieved if the PN sequence $\{b_n\}$ is defined such that the $\{a_n\}$ sequence is also a PN sequence. More particularly, the cross-correlation between the $\{a_n\}$ sequence and its shifted versions should be zero or low except when the two sequences are aligned. For the embodiment in which the M_n values are obtained based on the decision statistic shown in equation (11), the a_n values are simply equal to the b_n values for the PN sequence. In general, the a_n values are dependent on the manner in which the M_n values are obtained.

[0055] Peak detection is performed on the C_n correlation values obtained for different OFDM symbol periods to determine the start of a frame. A correlation peak appears when the M_n values are aligned with the a_n values. Peak detection may be performed in various manners. For example, the C_n correlation value for each OFDM symbol period may be compared against a threshold value, and a correlation peak may be declared whenever the correlation value exceeds the threshold value. As another example, a correlation peak may be declared whenever the C_n correlation value exceeds the average or the next highest correlation value by some amount.

[0056] The frame synchronization may also be performed to detect for the end of a frame or some other part of the frame. This can be achieved by selecting different portions of the sequence of a_n values corresponding to the part of the frame to be detected. In general, the correlation is between (1) M_n values for N_C OFDM symbol periods "marked' by the current OFDM symbol period n and (2) a_n expected values for the M_n values at a designated OFDM symbol period or portion of the frame.

[0057] For an AWGN channel, the correlation between M_n and a_n provides a gain of N_C (the length of the correlation) in the SNR of the C_n correlation value at the peak. Hence, robust detection for frame synchronization is possible even under poor SNR

conditions. The correlation length N_C can be selected based on various factors. A larger value for N_C provides greater gain in SNR and greater reliability in frame detection. However, more memory is needed to store the M_n values for the larger value of N_C.

[0058] To simplify the processing for frame synchronization, the M_n values may be quantized to L bits, where $L \geq 1$. For example, the M_n values may be quantized to one bit by performing hard decisions on these values. The quantized M_n values (denoted as $\hat{M}_n$) may be correlated with the a_n values as shown in equation (13).

[0059] If the pilot symbols are scrambled with the PN sequence as described above, then the pilot symbols cannot be recovered until frame synchronization has been performed and the start of the frame is known. The frequency-corrected pilot symbols $\tilde{P}_n(k)$ can then be descrambled by multiplying these symbols with the complex conjugate of the PN sequence. The channel gain $H_n(k)$ can be estimated based on the descrambled pilot symbols.

[0060] For step 320 in FIG. 3, data detection is performed on the frequency-corrected data symbols $\tilde{D}_n(k)$, as follows:

$$\hat{D}_n(k) = \frac{\tilde{D}_n(k)}{\hat{H}_n(k)} , \qquad \text{Eq (14)}$$

where $\hat{H}_n(k)$ is the channel gain estimate for subband k in symbol period n; and

$\hat{D}_n(k)$ is the detected data symbols for subband k in symbol period n.

The data detection may also be performed in other manners, as is known in the art. The detected data symbols for the frame are provided as one sequence for subsequent processing.

[0061] **FIG. 5** shows a flow diagram of a process 500 for performing integer frequency error estimation at the receiver in the OFDM system. Process 500 may be used for step 312 in FIG. 3.

[0062] Initially, a value for the metric $M_n(f)$ is computed for each of a number of hypothesized frequency errors based on the received symbols (block 510). This can be achieved by selecting a hypothesized frequency error $\tilde{f}$ for evaluation (step 512). For each pilot subband k, a cross-correlation is performed between two received symbols

obtained in two consecutive OFDM symbol periods on a hypothesized subband $k + \tilde{f}$ that is offset by $\tilde{f}$ from pilot subband k (step 514). A phase correction term may or may not be included in the cross-correlation, as shown in equations (3) and (10). The cross-correlation results for all pilot subbands are accumulated to obtain a decision statistic $A_n(\tilde{f})$ or $A_n'(\tilde{f})$ for the hypothesized frequency error $\tilde{f}$ (step 516). If all hypothesized frequency errors have not been evaluated (as determined in step 518), then the process returns to step 512 to selected another hypothesized frequency error for evaluation. Otherwise, a set of metric values is obtained from a set of decision statistics obtained for all hypothesized frequency errors that have been evaluated (step 520). The metric may be either the real part of the decision statistic or the entire decision statistic.

[0063] The frequency error is then estimated based on the set of metric values (block 530). This is achieved by computing the magnitude (or the square of the magnitude) of each metric value. The metric value in the set with the largest magnitude (or largest squared magnitude) is identified (step 532). The hypothesized frequency error for this identified metric value is provided as the estimated integer frequency error (step 534).

[0064] The integer frequency error estimation typically only needs to be performed once, for example, when the receiver first tunes to the transmitter or at the start of a data transmission after a long period of inactivity. Thereafter, the mechanism used to estimate and track out the fractional frequency error can be used to maintain frequency lock at the receiver.

[0065] **FIG. 6** shows a flow diagram of a process 600 for performing frame synchronization at the receiver in the OFDM system. Process 600 may be used for step 316 in FIG. 3.

[0066] Initially, a metric value M_n is computed for each OFDM symbol period based on the cross-correlation between two received symbols obtained in two consecutive OFDM symbol periods on each pilot subband, as described above (step 612). The metric value M_n is obtained after the integer frequency error f has been estimated and removed either pre-FFT or post-FFT. For each OFDM symbol period, a sequence of M_n values for N_C (e.g., most recent) OFDM symbol periods is correlated with a sequence of a_n values to obtain a C_n correlation value for the OFDM symbol period, as shown in equation (13) (step 614). The a_n values are the expected values for

the M_n values at the proper time alignment. Peak detection is then performed on the correlation values obtained for different OFDM symbol periods (step 616). Frame synchronization is declared when a correlation peak is detected (step 618). The detected correlation peak can correspond to the start of a frame or some other part of the frame, depending on the sequence of a_n values used for correlating.

[0067] The frame synchronization may be performed on a continual basis, e.g., for each frame. The frame synchronization may also be performed as needed, e.g., at the start of each data burst.

[0068] **FIG. 7** shows a block diagram of an embodiment of OFDM demodulator 160 at receiver 150 in FIG. 1. A pre-processor 710 receives and processes the input samples from receiver unit 154 and provides pre-processed samples. Pre-processor 710 may perform sample rate conversion, fractional and possibly integer frequency correction, cyclic prefix removal, and so on, as described below. An FFT unit 720 performs an FFT on the pre-processed samples for each received OFDM symbol to obtain received symbols $R_n(k)$.

[0069] A metric computation unit/frequency error estimator 750 estimates the integer frequency error at receiver 150 based on the metric $M_n(f)$ and the received symbols $R_n(k)$, as described above. Unit 750 provides the estimated integer frequency error $\hat{f}$ to either pre-processor 710 or a frequency correction unit 730. Pre-processor 710 can perform pre-FFT integer frequency correction, and frequency correction unit 730 can perform post-FFT integer frequency correction. A frame synchronization unit 760 receives M_n metric values from metric computation unit 750, performs frame synchronization based on these metric values, and provides a Frame Sync signal to a channel estimator 770. The Frame Sync signal indicates the start of each frame.

[0070] Frequency correction unit 730 provides frequency-corrected data symbols $\tilde{D}_n(k)$ to a data detector 740 and frequency-corrected pilot symbols $\tilde{P}_n(k)$ to channel estimator 770. Channel estimator 770 descrambles the frequency-corrected pilot symbols based on the Frame Sync signal, estimates the channel gain based on the descrambled pilot symbols, and provides channel gain estimates $\hat{H}_n(k)$ to data detector 740. Data detector 740 performs data detection on the frequency-corrected data symbols with the channel gain estimates as shown in equation (14) and provides detected data symbols $\hat{D}_n(k)$.

[0071] **FIG. 8** shows a block diagram of a specific design for OFDM demodulator 160. Within pre-processor 710, a sample rate converter 810 receives and converts the input samples (at the sampling rate) into interpolated samples (at the chip rate). The chip rate refers to the rate of the chips that make up the OFDM symbols at the transmitter. The sampling rate refers to the rate used by receiver unit 154 to digitize the received signal. The sampling rate is typically selected to be higher than the chip rate to simplify filtering at the receiver. A time acquisition unit 812 acquires the timing of the received OFDM symbols (e.g., based on the cyclic prefix), determines the boundaries of the received OFDM symbols, and provides timing signals to other processing units within OFDM demodulator 160 (not shown in FIG. 8 for simplicity). A fractional frequency error detector 814 estimates the fractional frequency error at the receiver based on the cyclic prefix in the interpolated samples. A phase rotator 816 applies fractional frequency error correction to the interpolated samples and provides frequency-corrected samples. A cyclic prefix removal unit 818 removes the cyclic prefix appended to each OFDM symbol by the transmitter and provides the pre-processed samples.

[0072] For the embodiment shown in FIG. 8, metric computation unit/frequency error estimator 750 uses the metric defined based on the cross-correlation method. Within unit 750, a correlator 850 performs cross-correlation on pairs of received symbols obtained in two consecutive OFDM symbol periods on a hypothesized subband $k+\tilde{f}$. For each hypothesized frequency error $\tilde{f}$, the cross-correlation is performed for each of the pilot subbands and may or may not take into account the phase correction for the hypothesized frequency error $\tilde{f}$. An accumulator/post-processing unit 852 accumulates the correlation results for all subbands for each hypothesized frequency error to obtain a decision statistic $A_n(\tilde{f})$ for that hypothesis. Unit 852 provides a metric value $M_n(\tilde{f})$ for each hypothesized frequency error based on the real part of the decision statistic $A_n(\tilde{f})$ or the entire decision statistic $A_n'(\tilde{f})$. Correlator 850 and accumulator 852 form the metric computation unit. A magnitude detector 854 detects for the metric value $M_n(\hat{f})$ with the largest magnitude for each OFDM symbol period. Detector 854 provides (1) the estimated frequency error $\hat{f}$ to frequency correction unit

730 or fractional frequency error detector 814 and (2) the M_n metric values to frame synchronization unit 760.

[0073] For the embodiment shown in FIG. 8, a correlator 860 within frame synchronization unit 760 correlates the M_n metric values with the a_n values and provides a correlation value C_n for each OFDM symbol period. A peak detector 862 performs peak detection on the C_n correlation values for different OFDM symbol periods and provides the Frame Sync signal.

[0074] For clarity, both frequency error estimation and frame synchronization have been described for an exemplary OFDM system. In general, the frequency error estimation techniques described above may be used independently of the frame synchronization. Furthermore, the frame synchronization techniques described above may be used independently of the frequency error estimation, which may be achieved in various manners. The frequency error estimation techniques, or the frame synchronization techniques, or both the frequency error estimation and frame synchronization techniques described herein may be used at the receiver, depending on its design.

[0075] The pilot transmission scheme described above supports both frequency error estimation and frame synchronization. Other pilot transmission schemes may also be used. For example, the pilot symbols may be transmitted in a non-continuous manner (i.e., only on designated OFDM symbol periods), on different subbands in different OFDM symbol periods, and so on. The pilot symbols do not need to be scrambled with the PN sequence for frequency error estimation. The metric is defined in a manner corresponding to and consistent with the pilot transmission scheme used by the OFDM system.

[0076] The frequency error estimation and frame synchronization techniques described herein may be implemented by various means. For example, these techniques may be implemented in hardware, software, or a combination thereof. For a hardware implementation, the processing units used to perform frequency error estimation and/or frame synchronization may be implemented within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), processors, controllers, micro-controllers, microprocessors, other electronic units designed to perform the functions described herein, or a combination thereof.

[0077] For a software implementation, the frequency error estimation and frame synchronization techniques may be implemented with modules (e.g., procedures, functions, and so on) that perform the functions described herein. The software codes may be stored in a memory unit (e.g., memory unit 182 in FIG. 1) and executed by a processor (e.g., controller 180). The memory unit may be implemented within the processor or external to the processor, in which case it can be communicatively coupled to the processor via various means as is known in the art.

[0078] The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

[0079] WHAT IS CLAIMED IS: